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The compatibility of diffractive hard scattering in $p\bar{p}$ and ep collisions

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Abstract

We show that the data for diffractive dijet production at the Tevatron $p\bar{p}$ collider are consistent with diffractive deep inelastic ep data collected at HERA. The breakdown of factorization between the two data sets is naturally explained by a strong tendency to populate the rapidity gap in the $p\bar{p}$ diffractive process by secondaries from soft underlying interactions and by bremsstrahlung associated with the presence of the hard dijet subprocess.

Nearly 40 years ago it was predicted that hadronic total cross sections would approach a constant asymptotic limit. The Regge trajectory whose exchange ensures this behaviour became known as the Pomeron, with intercept $\alpha(0) = 1$. Even today the observed slowly rising (high energy) total cross sections, and elastic scattering behaviour in the near forward direction, are remarkably well described by an effective trajectory $\alpha(t) \simeq 1.08 + 0.25t$, where t is the square of the 4-momentum transfer (in units of GeV^2). Nowadays this is known as the "soft" or "non-perturbative" Pomeron.

More recently, interest in Pomeron physics has been revived by studies of "diffractive events" in proton-proton collisions, which contain a rapidity gap in the final state, such that the hadrons produced in the collision only populate part of the detector away from the direction of one of the outgoing protons. A supplementary condition for the presence of soft Pomeron exchange

is that there should be a slow variation of the cross section as a function of the width of the rapidity gap. The recent interest dates from the Ingelman and Schlein conjecture [1] that there would also be "hard" diffractive events in which the final state contains jets as well as a rapidity gap, and that the Pomeron (associated with the gap) is treated as a real particle made up of quarks and gluons which take part in the hard subprocess. Such "hard" diffractive events have indeed been observed in high energy $p\bar{p}$ collisions, originally in the UA8 experiment [2] at CERN, and most recently by the CDF collaboration [3] at the Tevatron $p\bar{p}$ collider. The CDF collaboration study dijet production (for jets with $E_T > 7$ GeV) in diffractive events with a leading antiproton with a beam momentum fraction x_F in the interval $0.905 < x_F < 0.965$, at $\sqrt{s} = 1800$ GeV. For a given x_F the rapidity gap is $\Delta y \sim \ln(1/(1-x_F))$.

Similar hard diffractive events are seen in high energy deep inelastic electron-proton collisions in which the outgoing proton travels approximately in the original beam direction leaving a large gap between its rapidity and that of the other hadrons [4, 5]. We speak of diffractive deep inelastic scattering (DDIS). The DDIS cross section can be factorized [6] into a convolution of "universal" parton densities of the Pomeron (sometimes called diffractive parton distributions) with the partonic-level cross sections of the hard subprocess, see Fig. 1(a). This is in direct analogy with the parton model of ordinary DIS in which we measure the universal parton densities of the proton. Thus the HERA DDIS data may be used to constrain the parton densities of the Pomeron, see, for example, Ref. [4].

However it is found [7, 3] that when, as in Fig. 1(b), the parton densities of the Pomeron are used, together with the parton densities of the proton, to estimate the cross section for the hard diffractive dijet production observed in $p\bar{p}$ collisions, the factorized prediction turns out to be an order of magnitude larger than the data [3]. To be precise the average "discrepancy" in normalisation is

$$D \;\equiv\; \frac{\text{data}}{\text{prediction}} \;\simeq\; 0.06 \,\pm\, 0.02. \tag{1}$$

A similar "discrepancy",

$$D_W \;\simeq\; 0.18 \,\pm\, 0.04, \tag{2}$$

was found earlier between the predictions and the observations of diffractive W production in $p\bar{p}$ collisions [8].

A key assumption of the above factorization estimates is that the survival of the rapidity gap (associated with Pomeron, $I\!\!P$, exchange) is the same in Figs. 1(a) and 1(b). Here we emphasize that a breakdown of factorization is an evident consequence of QCD and occurs naturally due to the small probability,

$$\omega \;=\; S^2 T^2, \tag{3}$$

for the rapidity gap to survive in hadron-hadron collisions. First, there is the probability, $1-S^2$, that the gap in Fig. 1(b) may be filled by secondaries produced (via parton rescattering) in the underlying soft interaction; note that there is no such rescattering in DIS of Fig. 1(a). Second, there is the probability, $1-T^2$, that the gap will be populated by extra gluon emission associated with the presence of the hard subprocess in diffractive hadron-hadron collisions. A

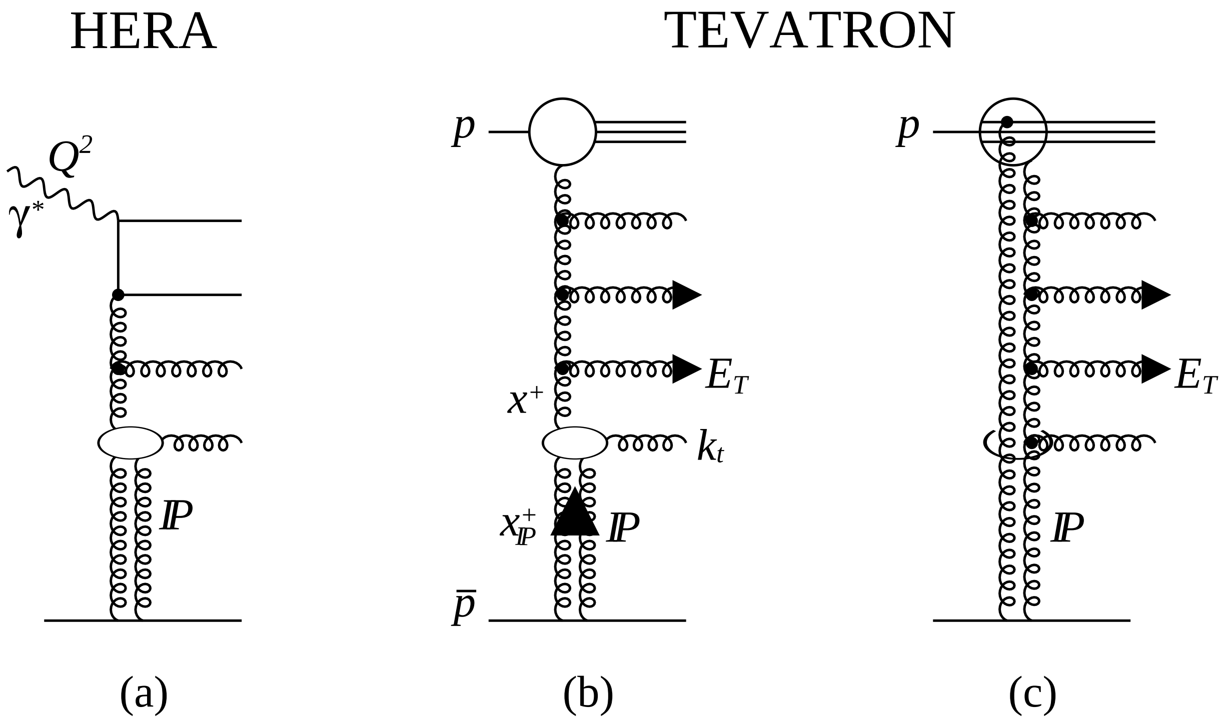

Figure 1: Diagrammatic representation of (a) diffractive DIS, (b) diffractive dijet production in $p\bar{p}$ collisions, and (c) an additional, non-factorizing, dijet production mechanism where the colour screening gluon couples to a spectator parton. In diagrams (a) and (b) the Pomeron is treated as a real particle and the process is mediated by a gluon input structure function of the Pomeron at scale k_t. E_T denotes the transverse energy of the hard jets emitted in the diffractive $p\bar{p}$ process.

similar form (3) of the survival probability was computed in Ref. [9] for the central production of a Higgs boson (and also of a dijet system) with a rapidity gap on either side. Of course the survival probability ω depends on the particular process, on the incoming energy, and on the final state configuration.

The probability not to have extra soft rescattering has been estimated to be $S^2 \sim 0.01 - 0.1$ for various processes at different collider energies [9]–[15]. We refer to Ref. [9] for our most recent calculation of S^2, using explicit models for soft rescattering; see also [16]. There it was found that the value of S^2 depends mainly on the optical density (or opacity) of the $p\bar{p}$ interaction as a function of the impact parameter ρ_T. Briefly, the survival probability S^2 was calculated from

$$S \;=\; \langle \exp(-\Omega(\rho_T)/2) \rangle \tag{4}$$

where the average was taken over the ρ_T dependence, and the opacity was assumed to have the Gaussian form

$$\Omega(\rho_T) \;=\; \frac{C^2 \sigma_0 (s/s_0)^\Delta}{2\pi B}\; \exp(-\rho_T^2/2B), \tag{5}$$

where the slope of Pomeron exchange amplitude

$$\tfrac{1}{2}B \;=\; B_0 \;+\; \alpha'_{I\!P}\,\ln(s/s_0), \tag{6}$$

and C specifies the amount of anti(proton) dissociation in the rescattering process. The parameters σ_0, B_0, Δ and $\alpha'_{I\!P}$ of the eikonal model were tuned to describe the behaviour of the total and elastic differential pp (or $p\bar{p}$) cross sections throughout the ISR to Tevatron energy range ($30 < \sqrt{s} < 1800$ GeV). Taking the mean value of ρ_T to be the proton radius, it was found [9] that $S^2 \sim 0.1$ at the Tevatron energy (and up to an order of magnitude smaller still at LHC energies).

The factor $S^2 \sim 0.1$ in (3) explains the main part of the "discrepancy" reported in Ref. [3]. Some indication in favour of a small survival probability ($S^2 \lesssim 0.1$) has also been observed by the D0 collaboration [17] in the process with two large E_T jets separated by a rapidity gap. Furthermore, there is a plausible explanation why $D < D_W$, as seen in (1) and (2). The optical density is smaller in the periphery of the proton. On the other hand there are indications that the radius of the spatial distribution of quarks in the proton is larger than that for gluons[1]. Since the W boson is produced dominantly by quarks, whilst high E_T dijets originate mainly from gluons, we expect the survival probabilities of diffractive production to satisfy

$$S^2(W) \;>\; S^2(\text{dijet}). \tag{7}$$

Using (4)–(6) we may estimate how S^2 depends on the size of the rapidity gap. For the triple Pomeron process shown in Fig. 1(b)

$$\langle \rho_T^2 \rangle \;=\; b_0 \;-\; 2\alpha'_{I\!P}\ln(s/M^2), \tag{8}$$

where M is the invariant mass of the outgoing state produced by the $I\!Pp$ system. Thus, for example, as $x_F \to 1$ and the size of the gap increases (that is $s/M^2 = 1/(1-x_F)$ increases), slightly smaller values of ρ_T are sampled and this, in turn, gives a little smaller S^2. However this is not a strong effect, since $\langle \rho_T^2 \rangle$ is dominated by b_0 (which is independent of s/M^2 and determined mainly by B_0).

On the other hand the data show some β dependence, where β is the momentum fraction of the Pomeron entering the hard subprocess, $\beta = x^+/x^+_{I\!P}$ of Fig. 1(b). The CDF collaboration plot the discrepancy D as a function of β (see Fig. 4 of [3]). They observe that D decreases with increasing β. The β dependence can be attributed to the behaviour of the survival factor T^2 of the rapidity gap against bremsstrahlung associated with the presence of the hard subprocess in Fig. 1(b). The result depends on the scale k_t at which the gluon structure function of the Pomeron is sampled. Note that in Fig. 1(b) the lowest emitted gluon along the chain has transverse momentum close to k_t, whereas the hard jets have transverse energy E_T.

[1]A comparison of the slope of diffractive J/ψ photoproduction ($b \simeq 4$ GeV^{-2}) with the behaviour of the proton electromagnetic form factor ($b \simeq 5.5$ GeV^{-2}), indicates that gluons have a smaller spatial extent than quarks. A similar conclusion follows from a study of QCD sum rules [18]

The bremsstrahlung into the rapidity gap can originate from either the hard subprocess or associated with the Pomeron. First, consider bremsstrahlung from one of the hard E_T jets. When $\beta \to 0$, the hard jets are far from the rapidity gap and so there is no radiation into the gap and no suppression of the diffractive process. On the other hand, when $\beta \to 1$ one of the large E_T jets becomes the lowest gluon in Fig. 1(b), k_t, and bremsstrahlung will populate the gap, which is now adjacent in phase space. In this limit, if E_T is sufficiently large, the suppression is, in principle, calculable from perturbative QCD, but will be sensitive to the experimental jet-searching algorithm.

Now consider the $\beta \to 0$ and $\beta \to 1$ limits for bremsstrahlung associated with the Pomeron. For $\beta \to 0$, the scale k_t^2 of the Pomeron structure function is soft. There may be emission into the gap, but it is not calculable perturbatively. However, in this limit, it is the same Pomeron, with the structure function, and the same emission, as that measured in diffractive DIS at HERA, and so there is no *extra* suppression in the diffractive $p\bar{p}$ process. The situation is quite different for $\beta \to 1$, for which the scale $k_t \sim E_T$. The configuration of the two t-channel gluons forming the Pomeron is now asymmetric and we have more emission into the gap than in DDIS[2]. In fact for sufficiently large E_T (~ 50 GeV), the suppression of the diffractive $\bar{p}p$ process, arising from emission from the asymmetric gluon configuration of the Pomeron, can be estimated from perturbative QCD (see [9]).

In conclusion we have a qualitative understanding of the β dependence. For $\beta \to 0$ we expect (in comparison to DDIS) little extra suppression of the diffractive $p\bar{p}$ process from *bremsstrahlung* either from the hard subprocess or from the Pomeron. That is $T^2 \simeq 1$ in this limit. For increasing β, the suppression due to radiation increases (and $D(\beta)$ decreases) and, in fact, becomes calculable as $\beta \to 1$ if E_T is sufficiently large (with the Pomeron structure function providing an effective infrared cut-off via a factor $(1-\beta)^n$, where $n(k_t, E_T)$ is perturbatively calculable). Although the discussion of the β dependence has necessarily been qualitative, it is encouraging that the main trend is clearly seen in the data, see Fig. 4 of [3]. In fact we may identify $D(\beta) \sim 0.1 - 0.15$ for $\beta \lesssim 0.1$ with the survival factor S^2, since for $\beta \to 0$ we expect $T^2 \approx 1$. At present it is not possible to make a reliable comparison of diffractive $p\bar{p}$ and DDIS data much below $\beta \sim 0.1$, since there are no DDIS measurements in this region.

Although the survival factor S^2 is responsible for the main breakdown of factorization, we note that there is another non-factorizing contribution in diffractive $p\bar{p}$ collisions[3]. Besides the graph of Fig. 1(b) in which the second t-channel gluon (which screens the colour flow in rapidity gap interval) couples to a parton in the Pomeron fragmentation region (near the gap edge), there is also the possibility that the screening gluon couples to a fast spectator in the proton fragmentation region, see Fig. 1(c). Typically in such a configuration the colour flow is screened at larger distances and we deal with large size components of the Pomeron, so this

[2]For DDIS at scale $Q^2 \sim E_T^2$, it is possible to have Pomeron configurations with a large k_t quark, but for gluons in DDIS we still have $k_t \ll E_T$.

[3]It was noted in [6, 19] that factorization is not valid in $p\bar{p}$ collisions. A discussion can be found, for example, in the review of Ref. [20].

contribution leads to a larger diffractive (dijet) cross section. As a consequence the true value of the "soft" survival probability S^2 should be less than the estimate $S^2 \sim 0.1 - 0.15$ quoted above. The conclusion from the CDF data is therefore consistent with the estimate $S^2 \sim 0.1$ at the Tevatron energy obtained from the soft rescattering model.

It has recently been shown [21] that the ep [4, 5] and $p\bar{p}$ [3] diffractive hard scattering data can be described in terms of the Soft Colour Interaction [22] and Generalized Area Law [23] models. The unified description is obtained by implementing these models in the Monte Carlo generators LEPTO [24] for ep and PYTHIA [25] for $p\bar{p}$. However this 'soft colour' approach leads to a somewhat flatter β dependence than is observed for the CDF diffractive data, when the model is tuned to describe the deep inelastic ep data[4]. Our approach is different. Here we emphasize, qualitatively, that the $p\bar{p}$ and ep hard diffractive data have been presented in Ref. [3] in a way which demonstrates rather directly the role played by the survival probability factors S^2 and T^2 of (3), and which allows physical insight into the interpretation of the diffractive data.

In summary, we have shown that the data for hard scattering processes containing a rapidity gap in $p\bar{p}$ collisions at the Tevatron and the data for diffractive DIS collected in ep collisions at HERA, are compatible with each other. The QCD factorization approach appears to lead to an order of magnitude discrepancy between the data sets [3]. However the breakdown of factorization is naturally explained by the much smaller chance of the rapidity gap surviving in $p\bar{p}$ collisions as compared to ep interactions. Indeed the size, and β dependence, of the suppression of diffractive dijet production seen at the Tevatron [3] is just what is expected from the population of the rapidity gap by underlying soft interactions and from bremsstrahlung associated with the presence of the hard subprocess.

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[4]Note that an important part of $\omega = S^2T^2$ gap survival factor is automatically included in PYTHIA, which accounts for the possibility of soft rescattering in the underlying event (the factor S^2) and the bremsstrahlung in the 'hard' subprocess (part of the T^2 factor). However the Soft Colour model does not account for bremsstrahlung from the two-gluon dipole Pomeron state. That is why x^+ (or β) dependence in [21] is flatter than that observed by CDF [3].

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